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PRESTRESSED CONCRETE SHELL ROOF CONSTRUCTION

VORGESPANNTE DÜNNE BETON-SCHALEN

VOÛTE MINCE EN BÉTON, AVEC PRÉCONTRAINTE

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a) Introduction

Considerable interest has been created by the successful design and construction in the U. S. A. of a large number of shallow spherical gunite or concrete shell roofs in connection with new methods of prestressing. In the following a brief outline of the principles of design and the methods of construction of such shallow domes, is presented.

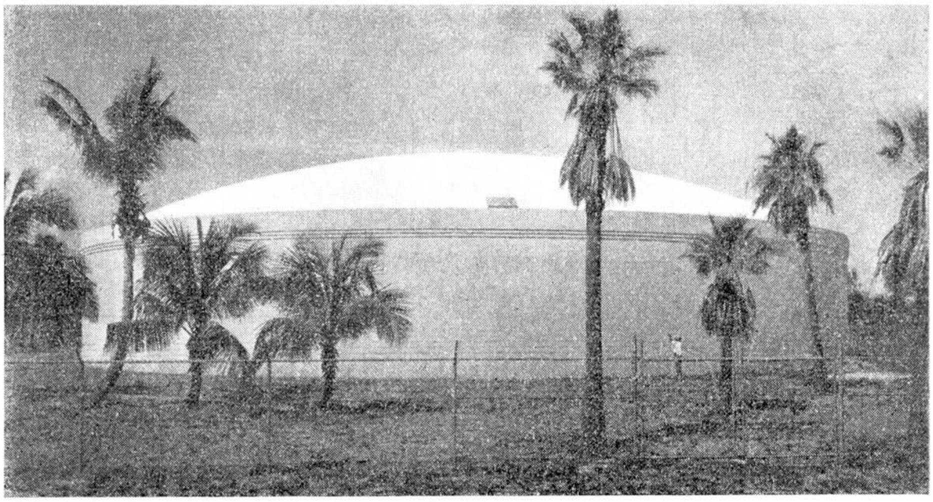

Fig. 1.
Miami Tank Dome Roof 1945 — Schalendach eines Tankes in Miami 1945 — Voûte sphérique pour réservoir, construite à Miami en 1945.

It has long been recognized that thin spherical shells have a great load carrying capacity. In practise, however, the use of shells as structural members has been greatly handicapped by the difficulty to create suitable edge or boundary conditions in the finished structure and during various stages of construction. The more recent developments in the prestressing of concrete have made possible the economic construction of relatively shallow dome shell roofs. In particular the „Preload" method of prestressing circular structures provides a powerful means of purposely introducing controlled forces and moments thus creating almost any desired edge movement.

Fig. 1 shows a typical prestressed concrete dome 3½" thick with a span of 128 ft. covering one of two 2½ million gallon tanks built for the Dept. of Water & Sewers of the City of Miami in 1945.

b) Prestressing of dome ring

The majority of the several hundred dome roofs constructed in the U. S. A. within the last 5 years consist of a segment of a thin spherical shell with large radius of curvature and a dome ring at the base of this shell. Both dome ring and shell are monolithic. The dome ring transmits prestressing forces and serves as an edge stiffening member preventing undue distortion of the shell edge under unsymmetrical loading conditions. Prestressing is achieved by spirally wrapping the outside face of the dome ring with high carbon steel wire under a constant predetermined stress of 140 000 psi. The dome ring and portions of the adjoining shell are thereby precompressed.

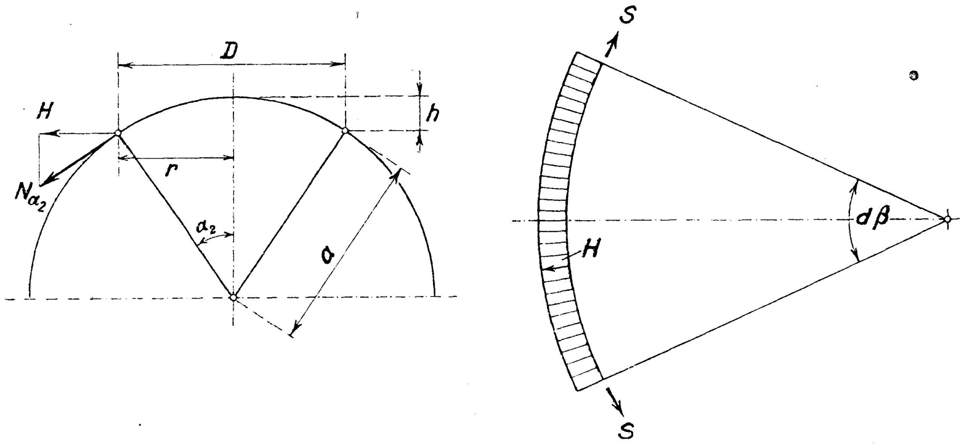

Fig. 2.
Dome Dimensions — Kuppelabmessungen — Dimensions de la voûte sphérique.

The design of conventional shell structures is usually based on the so-called „Membrane Theory“ of shells which assumes an infinitely thin shell capable of resisting stresses and shears within the surface of the shell only. This pure shell action under uniform load takes place in the major portion of the dome shell where the influence of discontinuity or edge restraint is insignificant.

Fig. 2 shows the top portion of a spherical shell with a central angle α_2, a diameter D, a radius of curvature a, and the forces N_α (or H respectively) which must be kept in equilibrium by the dome ring. The horizontal component H of N_α is creating a ring tension S. For equal load and diameter the magnitude of this ring tension is only governed by the angle α_2. For shallow domes of large span this ring tension force becomes excessive for a conventional concrete dome. Ordinary reinforced concrete dome rings are obviously unsuitable as cracking cannot be prevented except by most uneconomical proportions.

Prestressing of the dome ring eliminates these restrictions. The prestressed design assures that a residual compression remains in the concrete of the dome ring under the worst loading condition and after all shrinkage and plastic flow has taken place.

c) Influence of prestressing on the design of shallow spherical concrete shells

The main advantage of using shallow prestressed dome shells is the possibility to exclude all membrane tension stresses due to uniform load.

Fig. 3 shows how the meridional and the circumferencial membrane forces (N_α and N_β respectively) vary along a meridian of the shell. The meridional stresses remain compressive, whereas the ring stresses diminish progressively from a compressive value at the top of the shell to a zero point at a certain angle α^*. This critical angle α^* is a constant for each loading case, namely:

$$\text{Dead load } \alpha^* = 51^0 50'$$
$$\text{Live load } \alpha^* = 45^0$$

Tensile ring stresses can therefore be avoided by making $\alpha_2 \leqq \alpha^*$. This condition is fulfilled for uniformly distributed load if the rise (h) of the dome is less than approximately one-fifth of the diameter (D). Shallow dome shells also have the advantage of a smaller surface area which requires less scaffolding and formwork. An economical and practical ratio of rise (h) to diameter (D) is 1 to 8.

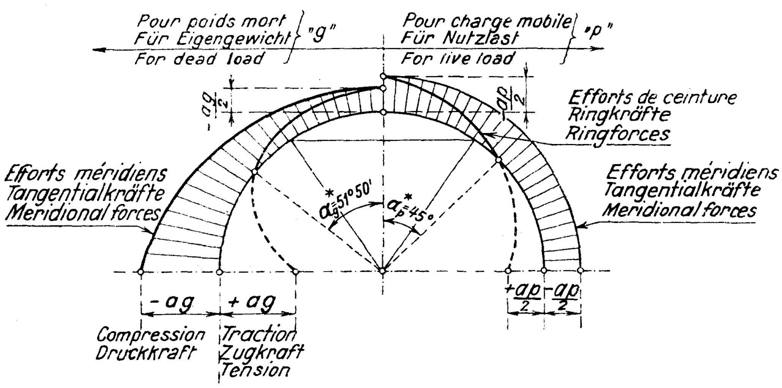

Fig. 3.
Membrane Forces — Membrankräfte — Efforts de membrane.

The membrane forces N_α, N_β, the radial deformation Δr_α and the angular turn ϑ are functions obtained in the classic „membrane theory“ [1]) as conditions of equilibrium between external loads and interior forces of a differential shell portion. Prestressing of the dome ring has no effect on these direct stresses except in the edge zone of the shell. (See tabulation of stresses. Table II.)

For normal loads the membrane or direct shell stresses are usually not higher than 200 to 300 p. s. i. and are well within safe limits as established through the strength of material and the stability of the shell even for shallow dome shells.

Near its edge the shell is forced to follow the deformations of the dome ring. Bending moments and shears normal to the shell surface are produced thereby. The resulting bending stresses and corrective direct stresses are calculated by the „bending theory“ of shells [1]). To ascertain the influence of prestressing the established „bending theory“ of shells is applicable. The

[1]) See Bibliography.

prestressing force creates an artificial edge movement which must be included in the condition of compatibility at the edge, similar to movements caused by dead load, live load, temperature and shrinkage. Thus the influence of prestressing on the stresses in the shell is classified simply as a modification of the boundary condition.

Meridional bending in spherical shells of uniform thickness is for practical purposes governed by the same basic differential equation as the bending of a beam on elastic foundation:

$$\vartheta'''' + 4k^4 \times \vartheta = 0 .$$

Solutions can be written through the use of exponential functions. The moments and shears are then represented by damped waves whose amplitudes rapidly decrease with increasing distance from the edge and according to the dampening factor „K".

$$K = \sqrt[4]{3(1-\mu^2)} \sqrt{\frac{a}{t}} .$$

where μ = Poisson's Ratio and t = thickness of shell.

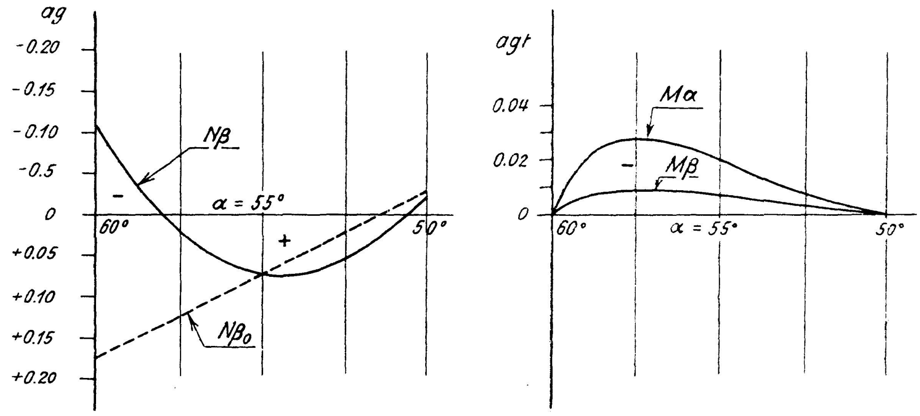

Fig. 4.
Direct Forces and Bending Moments in Shell Hinged at the Edge — Normalkräfte und Biegungsmomente in gelenkig gelagerten Schalen — Efforts normaux et moments fléchissants dans une coupole circulaire articulée à l'appui.

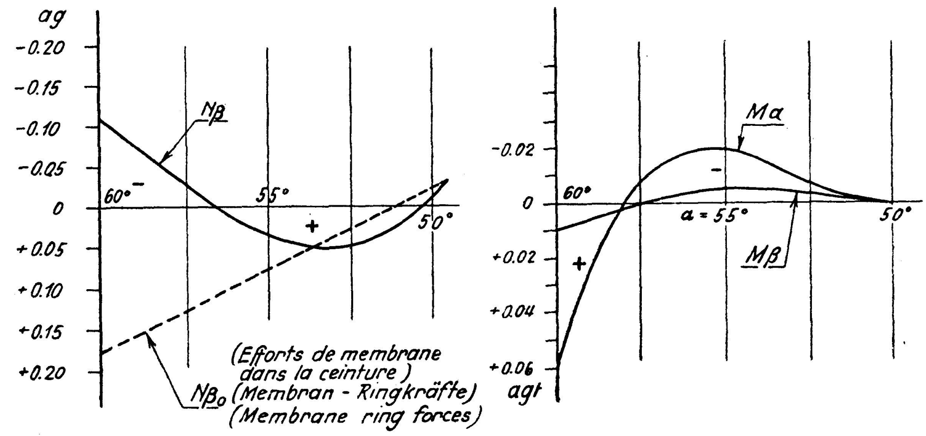

Fig. 5.
Direct Forces and Bending Moments in Shell Completely Fixed at the Edge — Normalkräfte und Biegungsmomente in vollständig eingespannten Schalen — Efforts normaux et moments fléchissants dans une coupole circulaire entièrement encastrée.

Fig. 4 and Fig. 5 show direct forces and bending moments for dead load in a spherical shell hinged at the edge and in one completely fixed at the edge.

The scope of this paper does not permit the presentation of the complete bending theory of shells with the inclusion of a prestressing force. The necessary equations are furnished by the principle of satisfying the compatibility requirements between movements of the shell edge and those of the prestressed dome ring.

Except in the simplest cases properly formulated mathematical expressions describing various conditions of stiffness and restraint at the shell edge would lead to undue mathematical complexity. Simplifying assumptions must therefore be made. It seems, therefore, fully justified also to make reasonable approximations in the stress analysis itself.

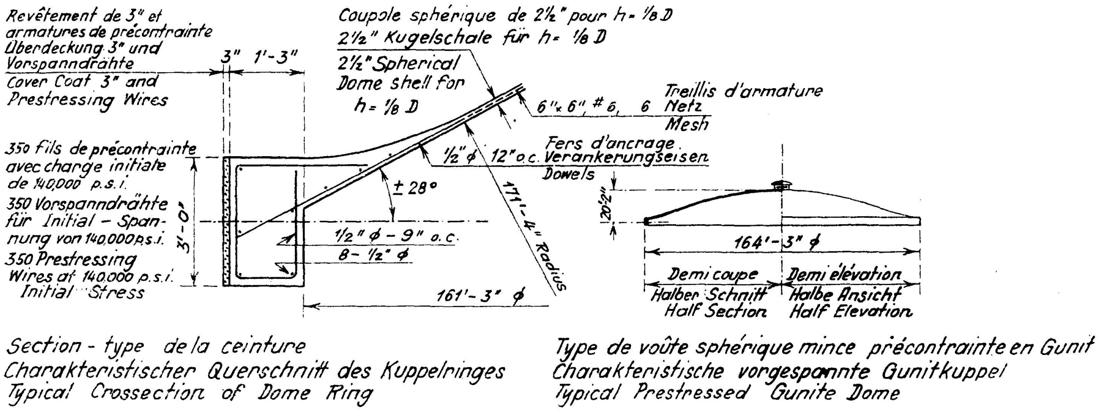

Fig. 6.

Typical Crossection Halifax Dome Roof — Charakteristischer Querschnitt eines Schalendaches in Halifax — Section droite caractéristique de la voûte Halifax.

Fig. 6 for instance shows a crossection through a typical dome ring. It is monolithically connected to the 2½" thick shell which is thickened at the edge to allow a more gradual change of stiffness and to provide for edge bending. The actual area and shape of the dome ring is therefore not a mere rectangle but must include portions of the shell edge. The interaction of dome ring and dome shell must therefore be estimated through the use of reasonable simplifacations.

For preliminary purposes the dome shell is assumed to be of uniform thickness throughout and monolithically connected to a dome ring of rectangular crossection ($b \times h$). Frequently the dome ring itself is monolithically connected to other structural members, such as cylindrical tank walls. The degree of participation of dome shell, dome ring and cylindrical wall shell in the transfer of loads and of prestressing forces is measured by the relative stiffness of each member against rotation and against horizontal deformation of the edge. The stiffnesses are the inverse ratios of the edge deformations or edge rotations.

The stress condition of the spherical shell can be calculated by introducing redundant forces (H) and moments (M) at an imaginary cut between the shell and dome ring and of equal magnitude and opposite sign (see Fig. 7).

Table I. Tabulation of deformations.

Loading	Spherical shell	Dome ring
$M = 1$	$\tau_M = \frac{a}{K} \frac{12(1-\mu^2)}{E \times t^3}$	$\tau_M = \frac{12 r^2}{E b h^3}$
	$\Delta r_M = -\frac{2K^2}{Et} \sin^2 \alpha_2$	—
$H = 1$	$\Delta r_H = \frac{2Ka}{Et} \sin^2 \alpha_2$	$\Delta r_H = \frac{r^2}{E b h}$
	$\tau_H = \Delta r_M$	—
Uniform dead load "g"	$\Delta r_g = \frac{ag \sin \alpha_2}{Et} \left\{ \frac{(1+\mu)}{(1+\cos \alpha_2)} - \cos \alpha_2 \right\}$	$\Delta r_g = -\Delta r_H \times \frac{ag \times \cos \alpha_2}{(1+\cos \alpha_2)}$
	$\tau_g = -\frac{ag}{Et}(2+\mu) \sin \alpha_2$	—
Uniform live load "p"	$\Delta r_P = \frac{a^2 p \sin \alpha_2}{Et} \left\{ \frac{(1+\mu)}{2} - \cos^2 \alpha_2 \right\}$	$\Delta r_p = -\Delta r_H \times \frac{ap \cos \alpha_2}{2}$
	$\tau_P = -\frac{a \times p}{Et}(3+\mu) \sin \alpha_2 \cos \alpha_2$	—
Centric prestressing force P	—	$\Delta r_P = \frac{r^2}{E b h} \times P$
Excentric prestressing force $P \times e = M_P$	—	$\tau_P = \frac{r^2}{E I_P} \times M_P$
Loss of prestress ΔP due to shrinkage plastic flow and other causes	—	$\Delta r_{\Delta P} = \frac{r^2}{E b h} \times \Delta P$
	—	$\tau_{\Delta P} = \frac{r^2}{E I_p} \times \Delta M_P$
	—	where $\Delta P = \frac{\alpha_s}{r} E b h$
Uniform $\left\{ \begin{matrix} \text{rise} \\ \text{fall} \end{matrix} \right\}$ of temperature Δt	$\Delta r_t = \alpha_t \times \Delta t \times a \sin \alpha_2$	$\Delta r_t = \alpha_t \times \Delta t \times r$
	$\tau_t = 0$	$\tau_t = 0$
Shrinkage	$\Delta r_s = \alpha_s \times a \sin \alpha_2$	$\Delta r_s = \alpha_s \times r$
	$\tau_s = 0$	$\tau_s = 0$

$$\alpha_s = \varepsilon_s = \frac{\Delta r_s}{r} = \frac{f_c}{E} = \frac{\Delta P}{bhE} \qquad \Delta P = bhE\alpha_s$$

In order to fulfill the requirements of compatibility at the edge of the shell for a rotation τ and translatory movement Δr, the following equations must be satisfied:

$$\Delta r_0 + H \times \Delta r_H + M \times \Delta r_M = 0$$

$$\tau_0 + H \times \tau_H + M \times \tau_M = 0$$

In these equations, the subscript „0" indicates a deformation due to external loads and prestressing, and subscript „H" or „M" deformations due to unit redundants H and M respectively. Each of the total deformations in the above equations contains two contributions, one from the dome ring and one from the dome shell which must be combined with the proper signs according to their respective direction. For convenience, movements and rotations are called positive in the direction of H or M, respectively.

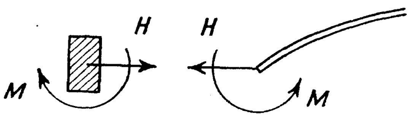

Fig. 7.

Redundants — Überzählige Größen — Grandeurs hyperstatiques.

The influence of the prestressing force P can best be appreciated when the redundants H and M are numerically calculated for a specific example and by earmarking contributions from various loads. In the following, we give a tabulation of stresses calculated for the 164′ dome [2]) shown in Fig. 6 and 11:

Table II.

Tabulation of stresses at edge of 164′ dome (Fig. 6) rigidly connected to dome ring and supporting wall.

		Load	Membrane stresses	Corrective direct stresses due to bending	Total direct stresses	Bending stresses Outside face Inside face	Total direct plus bending stresses	
							Outside face	Inside face
Radial	Before vol. changes	g	−91	+7	−84	±250	+166	−334
		p	−172	+12	−160	±442	+282	−602
		P		−20	−20	∓707	−727	+687
		$-\Delta P$		+6	+6	±202	+208	−196
		$g+P$	−91	−13	−104	∓457	−561	+353
		$g+p+P$	−263	−1	−264	∓15	−279	−249
	After	$g+P-\Delta P$	−91	−7	−98	∓255	−353	+157
		$g+p+P-\Delta P$	−263	+5	−258	±187	−71	−445
Circumferential	Before vol. changes	g	−61	+140	+79	±42	+121	+37
		p	−96	+248	+152	±72	+224	+80
		P		−395	−395	∓118	−513	−277
		$-\Delta P$		+112	+112	±34	+146	+78
		$g+P$	−61	−255	−316	∓76	−392	−240
		$g+p+P$	−157	−7	−164	∓4	−168	−160
	After	$g+P-\Delta P$	−61	−143	−204	∓42	−246	−162
		$g+p+P-\Delta P$	−157	+105	−52	±30	−22	−82

(positive stresses are tensile)

Note: Prestressing Force P includes a 40 % increase over and above that required for dead load and live load in order to compensate for prestress losses due to shrinkage, plastic flow and other causes.

$$\Delta P = \cdot 285 \times P$$

[2]) See Journal of the Am. Water Works Association, June 1947.

While this example does not yet include influences due to „eccentric" prestressing, it nevertheless indicates the importance of the uniform prestressing force in eliminating tensile stresses in the shell and dome ring.

A number of interesting studies are under way to include the influence of a thickening of the dome shell at the edge and to evaluate the effect of eccentric prestressing.

A theoretical analysis of prestressed spherical dome shells on point supports has been prepared [3]) and awaits corroboration by laboratory and field tests.

It was recognized early that, in the construction and design of dome shells, it is desirable to avoid non-uniform or concentrated loads. However, this is not always possible. Concentrated loadings are frequently applied due to machinery on top of a dome, particularly in the construction of industrial or sanitary tanks. A very comprehensive stress analysis and a series of model tests for this loading case have been made in 1943 for the Preload Corp. in New York by Prof. ERIC REISSNER, Prof. A. G. DIETZ, Prof. H. R. STALEY and Prof. W. C. VOSS of the M. I. T. [4]). The report contains a series of curves for direct and bending stresses for various spot loading and various edge conditions. In general, the bending effect of concentrated loads is local in character and disappears rapidly with increasing distance from the origin and with decreasing stiffness of the shell.

d) Construction methods for prestressing

In principle, prestressing of concrete consists of imparting an initial compression stress to the concrete by means of stretching special reinforcing steel. This is accomplished either before the set of the concrete or, if after hardening, through elimination of bond between concrete and steel. Under load, the prestressed concrete will not crack, as in the case of conventionally reinforced concrete. The inability of concrete to take appreciable tension stresses has always been a handicap for reinforced concrete design.

An essential prerequisite for effective prestressing is the use of a high yield point steel. Failures of prestressing attempts in the early days of its development have been due to the use of relatively low yield point steel, which made it impossible to adequately allow for steel stress losses due to shrinkage, plastic flow and elastic deformations.

Considerable research has been done to ascertain separately the amount of shrinkage and plastic flow as functions of time. While shrinkage depends largely upon the water cement ratio and curing conditions, the plastic flow is also a function of the age at loading and of the sustained stress in the concrete. Several authors have proposed methods of approximately forecasting these influences [5]). However, for practical purposes it has been found adequate to design for a minimum and a maximum total amount of steel stress loss at the initial and the ultimate stress condition in the structure.

Authorities generally agree that the total steel stress loss due to shrinkage and plastic flow of concrete and due to a small amount of plastic set in the prestressing steel is in the neighbourhood of from 25000 to 35000

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[3]) By Prof. F. B. HILDEBRAND of the Massachusetts Institute of Technology, Cambridge, Mass, for Preload Corporation, New York, U. S. A.

[4]) Published in Journal of Mathematics and Psysics, vol. XXV, No. 4, Jan. 1947.

[5]) See papers on prestressing, plastic flow and shrinkage by: H. SCHORER, PARSONS, RAYMOND E. DAVIS, O. GRAF, DOUGLAS MCHENRY, HOWARD R. STALEY and others.

p.s.i. It appears, therefore, that a total maximum steel stress loss of 40 000 p.s.i. as used in the design of prestressed dome rings and tanks is a safe and conservative amount. Steel for this purpose as used in the U. S. A. is a high carbon steel wire of 0.162″ diameter with a yield point in the neighbourhood of 170 000 p. s. i. and a minimum ultimate strength of 200 000 p. s. i.

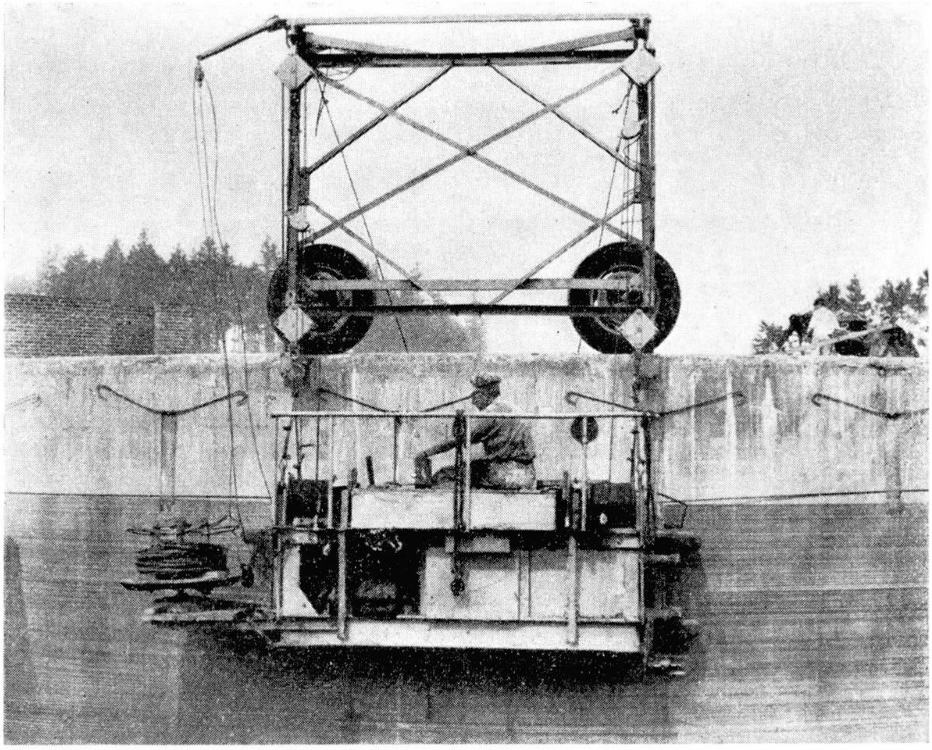

Fig. 8.
Wire Winding Machine — Drahtwinde — Machine pour poser le fil constituant la couronne de précontrainte.

A special machine has been developed by the PRELOAD CORPORATION of New York to apply the wire under a constant predetermined stress of 140 000 p. s. i. (see Fig. 8). The wire is stressed by passing it through a die of properly selected diameter. The die is mounted in a swivel die box of the wire winding machine. This machine is suspended by automatically adjustable cable pulleys from a supporting frame which travels on pneumatic tires on the dome ring and which is held upright by tie cables to a pin at the center of the dome. The machine is self-propelled by means of a traction cable and travels around the dome ring laying the wire under stress in closely spaced spirals. The endless traction cable passes through a tensioning device to maintain proper friction on the dome ring. The drive drum is operated on the same travelling platform by gasoline engines or in the lighter type wire winding machines by air motors.

The platform is mounted on a suitable frame held at a constant distance from the dome ring by 4 horizontal pneumatic tire wheels. It also carries a supply of wire on a reel and an operator who controls the clutch, the speed throttle or valve, and the vertical lifting device.

At the start, the wire is anchored in the concrete by means of anchor clamps. The winding proceeds at a speed of approximately 3 miles per hour, interrupted only for the purpose of splicing the end of a roll of wire to a new roll by means of a special torpedo splice (Fig. 9).

If more than one layer of wire is required, each layer is bonded after winding with a thin coat of gunite and the next layer is applied after the gunite is set. The last layer is covered with approximately one inch of gunite for permanent protection. The gunite cover so thoroughly bonds the wire to the dome ring that even if a wire should be cut the stress in the concrete corresponding to the cut wire would not be lost but would be transferred through horizontal shear into the adjacent wires. The required bonding length is very short as the prestressed wire will tend to increase its diameter where it is cut and form a plug or wedge. Breakage of a wire during the actual

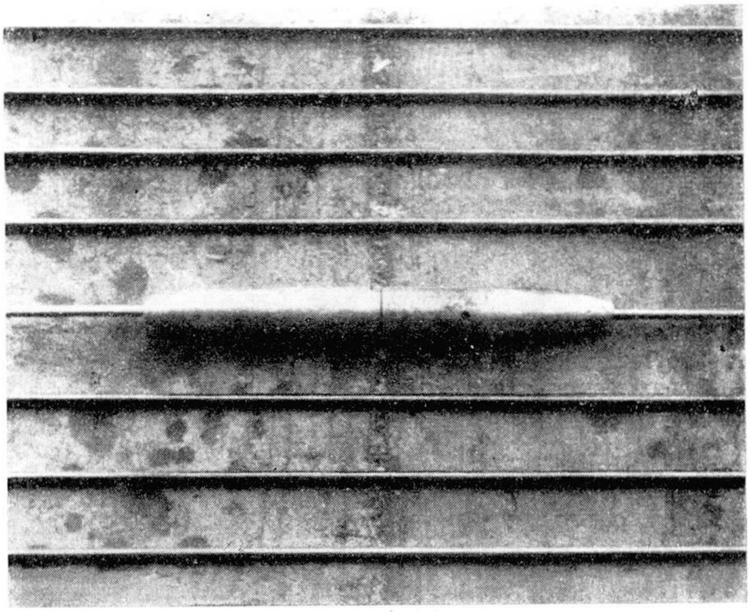

Fig. 9.
Torpedo Splice — Torpedo-Verspleißung — Epissure „Torpedo".

wire winding operation occurs seldom, but in order to prevent, in such a case, the whole spiral from loosing its stress, temporary anchor plates are installed at regular intervals. At the time of wire winding, the wire undergoes its supreme test at a stress which will never again be reached in service conditions. Wire stress increase due to live load cannot be larger than $n \times fc_{live\ load}$ and initial shrinkage usually more than offsets such an amount. During the prestressing operation, the dome ring is compressed and its radius is shortened in decrements corresponding to the number of layers of wire used. Due to this movement of the ring the dome shell lifts itself up, relieves the formwork of its load, and progressively all dead load is transfered to the dome ring.

After the completion of the wire winding, with an initial wire stress of 140 000 p. s. i., a total initial compressive stress of approximately 1000 p. s. i. has accumulated in the concrete of the dome ring. Ultimate working stresses after shrinkage and plastic flow are 100 000 p. s. i. in the wire and 700 p. s. i. compression in the concrete. If full live load is applied, these stresses will be 104 200 p. s. i. (for $n = 6$) in the wire and zero stress in the concrete.

The formwork (see Fig. 10) is usually erected with posts 10′ apart supporting concentric rings of beams on which radial ribs cut to the proper curvature are installed. Plywood, or ordinary 3/4″ sheeting is nailed diagonally across the ribs to make up the surface of the dome.

Fig. 10.
Formwork — Rüstung und Schalung — Coffrage.

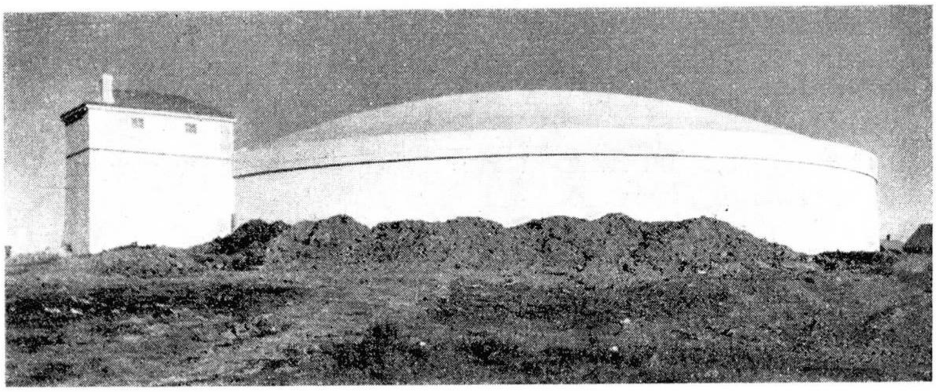

Fig. 11.
Halifax Dome Roof — Schalendach in Halifax — Voûte Halifax.

e) Conclusions

For the purpose of economically covering large areas without intermediate supports, the concrete dome shell roof is an ideal structural member particularly in connection with the latest techniques of prestressing.

The uselfulness of concrete dome shell roofs has been demonstrated in U. S. A. where the Preload Corporation in the last eight years has constructed over 200 reservoir roofs with spans up to 164 feet and in climates ranging from the semi-tropical to the severe winters of northern Canada (Fig. 11).

The cost of prestressed gunite dome shell roofs compares favorably with other types of construction. They can be built largely with local labor and materials and are practically maintenance free. The fact that concrete shell roofs are fireproof is an important consideration, especially in planning of airplane hangars and garages.

Designs are now being prepared for the use of large span prestressed spherical shell roofs for sports arenas, rural chain stores, and moving picture studios.

There is ample room for further development and as the structural action of prestressed spherical shells becomes better known, engineers will further avail themselves of their advantages.

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Summary

The combination of the existing theory on shell action with modern methods of prestressing circular structures has made possible the economic construction of relatively flat large span spherical dome roofs.

In the above a short outline is first given of the general theory of spherical shells. It is shown that the influence of a prestressing force at the base can be included in the analysis simply as a modification of the boundary conditions. — Numerical values of stresses due to dead load, live load, prestressing forces, shrinkage and plastic flow are given seperately to clearly demonstrate the importance of the prestressing force, as a means of eliminating tensile stresses.

In the last chapter the method of applying the prestressing wire under a constant predetermined stress is described. A self propelled machine rolling along the periphery of the dome ring spirally lays the wire on the ring. The stressing of the wire is performed by pulling it through a die mounted on the machine. Gunite is used to protect the wire against corrosion and to permanently bond it along its entire length to the prestressed structure.

Zusammenfassung

Die Kombination der modernen Schalentheorie mit den Methoden für vorgespannte kreisförmige Konstruktionen erlaubt den Bau von relativ dünnen Kugelschalen von großer Spannweite.

Der Verfasser gibt zuerst einen kurzen Überblick über die allgemeine Theorie der Kugelschale und zeigt, daß der Einfluß einer Vorspannung an der Basis in die analytische Berechnung auf einfache Weise eingeführt werden kann dadurch, daß man die Randbedingungen ändert. Es werden numerische Werte für die Spannungen infolge Eigengewicht, Nutzlast, Vorspannung, Schwinden und plastische Formänderung getrennt angegeben; dadurch gelingt es, den wichtigen Einfluß der Vorspannung als Mittel zur Ausschaltung der Zugspannungen deutlich aufzuzeigen.

Im letzten Teil bespricht der Verfasser die praktische Anwendung der vorgespannten Drahtkrone, die unter einer vorbestimmten konstanten Vorspannung maschinell aufgebracht wird. Der Vorspannungsdraht wird mittelst einer an der Basisperipherie entlang sich bewegenden Drahtzugmaschine vorgespannt und kontinuierlich unter Spannung aufgelegt. Ein Gunit-Überzug schützt den Draht vor Rost und bindet ihn auf seiner ganzen Länge in der vorgespannten Schale ein.

Résumé

La combinaison de la théorie actuelle de voûtes minces et des méthodes modernes de précontrainte des ouvrages circulaires a permis de réaliser économiquement la construction de voûtes sphériques relativement minces et de grande portée.

L'auteur expose tout d'abord brièvement la théorie générale des voûtes sphériques. Il montre que l'influence d'une contrainte préalable à la base peut être introduite dans l'étude analytique, sous une forme simple, par modification des conditions aux limites. Il donne séparément des valeurs numériques des contraintes dues au poids mort, à la charge utile, aux précontraintes, au retrait et à l'écoulement plastique, afin de mettre nettement en évidence l'importance de la contrainte préalable comme moyen d'élimination des contraintes de traction.

Dans la dernière partie, il expose les modalités d'application de la couronne en fil assurant la mise en jeu de la contrainte préalable, cette application se faisant sous une contrainte constante prédéterminée. Une machine spéciale se déplaçant automatiquement sur la périphérie de la base de la voûte pose le fil qui constitue cette couronne. La mise en contrainte du fil lui-même est réalisée par traction à travers une filière montée sur la machine elle-même. On a recours à la gunite pour assurer la protection du fil contre la corrosion et pour lier son assemblage de manière permanente, sur toute sa longueur, avec la voûte précontrainte.

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